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MEMORANDUM REPORT BRL-MR-3742

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APPLICATION OF COMPUTATIONAL FLUID DYNAMICS TO THE ANALYSIS OF THE AERODYNAMICS OF A RAILGUN PROJECTILE

PAUL WEINACHT

MARCH 1989

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release, distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) BRL-MR-3742	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION U.S. Army Ballistic Research Laboratory; 6b. OFFICE SYMBOL (If applicable) SLCBR-LF	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Aberdeen Proving Ground, Maryland 21005-5066	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62618A	1L162618AH80	00	001 AJ

11. TITLE (Include Security Classification)
APPLICATION OF COMPUTATIONAL FLUID DYNAMICS TO THE ANALYSIS OF THE AERODYNAMICS OF A RAILGUN PROJECTILE

12. PERSONAL AUTHOR(S)
WEINACHT PAUL

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Memorandum Report	FROM ____ TO ____		

16. SUPPLEMENTARY NOTATION

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP
01	01	
20	04	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Railgun Projectiles; Computational Fluid Dynamics, Parabolized Navier-Stokes, Railguns, Hypervelocity projectiles,

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

An existing computational capability has been applied to assess the aerodynamic performance of a novel railgun projectile currently being investigated. The viscous flow field over the railgun configuration has been computed using a Parabolized Navier-Stokes computational technique. The computations spanned a Mach number range from Mach 2 to Mach 8. Solutions have been obtained at zero and two degrees angle of attack, and pitch-plane aerodynamic coefficients and zero yaw drag coefficients have been determined. Using the computed pitch-plane aerodynamic coefficients, it was concluded that the proposed design is aerodynamically stable. Keywords: Hypervelocity trajectories, Supersonic characteristics, [illegible] characteristics.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
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DD Form 1473, JUN 86 Previous editions are obsolete.

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I. INTRODUCTION

An existing computational capability has been applied to assess the aerodynamic performance of a novel railgun projectile currently being investigated. Because to the approximations required to apply "design code" approaches to this non-axisymmetric geometry, Computational Fluid Dynamics (CFD) calculations have been performed to provide the projectile designer with more accurate aerodynamic information, without having to resort to wind tunnel testing. Previous studies[1,2] have demonstrated the accuracy of the computational capability for predicting the pitch-plane aerodynamics of axisymmetric boattailed shell and shell with non-conical boattails.

The projectile, shown schematically in Figure 1, consists of a conical nose with a non-conical aft section. The projectile also has a gap that runs through the body at the aft end of the projectile. The computational approach applied here necessitates that the gap be neglected. However, the effect of the gap has been estimated using the computed results. The nose of the projectile has a very small spherical nosecap of .008 calibers in radius. The spherical nosecap has not been modeled in the present analysis, and has been replaced by a conical tip. A previous study[3] has shown that small nose bluntness has little effect on the pitch-plane aerodynamics of shell at supersonic velocities. Computational approaches do currently exist for predicting the flow around the nose and in the gap. However, this degree of computational complexity and expense does not appear to be required or desired for the current design application.

In this report, the static pitch-plane aerodynamic coefficients (required to assess static stability of the projectile) are presented. Also included are predictions of the forebody drag coefficient. These results are presented in Section III. Preceding the discussion of the results is a brief description of the governing equations and computational technique applied in the current study.

II. GOVERNING EQUATIONS AND COMPUTATIONAL TECHNIQUE

Computation of the viscous flow field about the railgun projectile configuration is accomplished by solving the thin-layer Navier-Stokes equations using the Parabolized Navier-Stokes (PNS) technique. The thin-layer Navier-Stokes equations and the PNS computational technique are briefly described below.

1. THIN-LAYER NAVIER STOKES EQUATIONS

The set of equations that describes compressible viscous flow is referred to as the Navier-Stokes equations. These equations express the conservation of mass, momentum, and energy. The thin-layer Navier-Stokes equations, which are solved in this report, are obtained by eliminating from the full Navier-Stokes equations, all the viscous terms except for those containing derivatives in the direction nearly normal to the projectile body. For high Reynolds number flows with no axial flow separation, the thin-layer Navier-Stokes equations are very good approximation to the full Navier-Stokes equations, and can be efficiently solved using available numerical algorithms. In the current study, the cylindrical coordinate form of the governing equations have been cast in generalized coordinates.

The ideal gas law, which relates the pressure to the dependent variables, has been applied. It should be recognized that application of the ideal gas law at the higher Mach numbers is not strictly valid, though the effect on the aerodynamic coefficients considered here is thought to be small based on the results of a previous study[4].

The computations have been run for a turbulent boundary layer using the Baldwin-Lomax turbulence model[5].

2. THE PARABOLIZED NAVIER-STOKES PROCEDURE

The Parabolized Navier-Stokes (PNS) technique of Schiff and Steger[6] is widely used to compute the supersonic viscous flow about a variety of flight vehicles. By applying the PNS technique, the steady thin-layer Navier-Stokes equations can be solved using a procedure that allows the solution to be spacially marched along the body in the main flow direction due to the parabolic nature of the governing equations. An initial plane of data is required to begin the space marching procedure and may be obtained either from an auxiliary calculation or from a conical starting procedure, as has been done for the results presented here. Following the approach of Schiff and Steger, the governing equations are solved using a conservative, approximately factorized, implicit finite-difference numerical algorithm as formulated by Beam and Warming[7]. Further details of the procedure are readily available in the literature.

For the computational results presented here, the grid consisted of 60 points from the body to the shock and 37 points around the body for the half-plane solutions and 72 points for the full plane solutions. Shock fitting of the bow shock has been performed. Over the axisymmetric portion of the body, the grid was generated algebraically. On the non-conical portion of the body the grid was obtained using an elliptic grid generator. A section of the circumferential grid on the non-conical portion of the body is shown in Figure 2. A single half-plane computation of the flow field required approximately one hour of CPU time on a Cray-2 supercomputer.

III. RESULTS

Computation of the flow field over the railgun projectile has been performed for a series of Mach numbers between Mach 2 to Mach 8. Pitch-plane aerodynamic coefficients were determined by computing the flow field at two degrees angle of attack. The forebody drag coefficient was determined from flow field computations at zero degrees angle of attack. All solutions were computed for free flight (sea level) atmospheric conditions. In the results presented here, the aerodynamic coefficients have been non-dimensionalized using a diameter of 12.7 millimeters.

1. PITCH-PLANE AERODYNAMICS

Because of the non-axisymmetric nature of the projectile, angle of attack solutions were obtained at three different roll orientations with respect to the pitch-plane. These orientations are shown schematically in Figure 3. The results obtained for the roll orientation 1 are discussed first, followed by discussion of the effect of roll orientation. In the last section, estimation of the effect of the gap on the pitch-plane coefficients is discussed.

a. Roll orientation 1

The Mach number variation in the slope of the normal force and pitching moment coefficients is shown in Figures 4 and 5. The pitching moment is referenced to the center of gravity location. Both coefficients show a decrease with increasing Mach number.

The center of pressure, determined from the ratio of the pitching moment coefficient to the normal force coefficient, moves towards the nose with increasing Mach number as shown in Figure 6. The predicted center of pressure does remain aft of the center of gravity across the Mach number range of interest, as required for static stability. The static margin, shown in Figure 7, varies from a maximum of 11.8 percent at Mach 2 to a minimum of 8.0 percent at Mach 8.

b. Effect of roll orientation on the pitch-plane aerodynamic coefficients

Computations at angle of attack were performed for each of the three roll orientations shown in Figure 3. The resulting predictions of normal force and pitching moment coefficients as a function of Mach number are seen in Figures 8 and 9 respectively. The pitch-plane aerodynamic coefficients show very little variation between roll orientations, particularly at the higher Mach numbers. A tabulation of the computed coefficients as well as the predicted center of pressure and static margin is given in Appendix A.

c. Estimation of gap effect

As discussed previously, the computational results were obtained for a body without a gap, i.e., the gap that runs through the body at the aft end of the projectile has been ignored. Although computational techniques do currently exist for treating the gap, they are beyond the scope of the current study.

An attempt to estimate the effect of the gap on the pitch-plane aerodynamic coefficients has been made using the computed results for roll orientation 2. In this orientation, the pitch-plane is aligned with the gap and the effect of the gap on the pitch-plane coefficients is perceived to be greatest. In order to estimate the effect of the gap, the normal force and pitching moment coefficient were modified over the portion of the projectile where the gap exists. These coefficients were scaled by the ratio of the cross sectional area normal to the pitch plane with and without the gap. This was done to attempt to account for the loss of lifting surface produced by the presence of the gap.

Figure 10 shows the development of the normal force along the body at Mach 5 and two degrees angle of attack. The PNS prediction of the normal force is shown along with the results which include the estimated loss of normal force (lift) from the gap. The reduction in normal force over the portion of the projectile where the gap exists is clearly seen.

The estimated center of pressure obtained from the modified normal force and pitching moment coefficients is shown as a function of Mach number in Figure 11 along with the original computed results. As expected, the center of pressure moves forward due to the presence of the gap. The estimated center of pressure is still aft of the center of gravity location across the Mach number range, as required for static stability. Estimated static margin, shown in Figure 12, varies from 8.4 percent at Mach 2 to 5.7 at Mach 8, a reduction of about 40 percent over the solid body results. A tabulation of the estimated pitch-plane coefficients is shown in Appendix A.

It should be noted that the center of gravity used to compute the static margin is based on the actual configuration with the gap. Closing the gap could move the center of gravity aft, reducing stability. Clearly, there is a trade-off between filling the gap (ideally with lightweight non-conductive material) and causing the center of gravity to move aft, and allowing the gap to remain and having the center of pressure move forward relative to the solid body position.

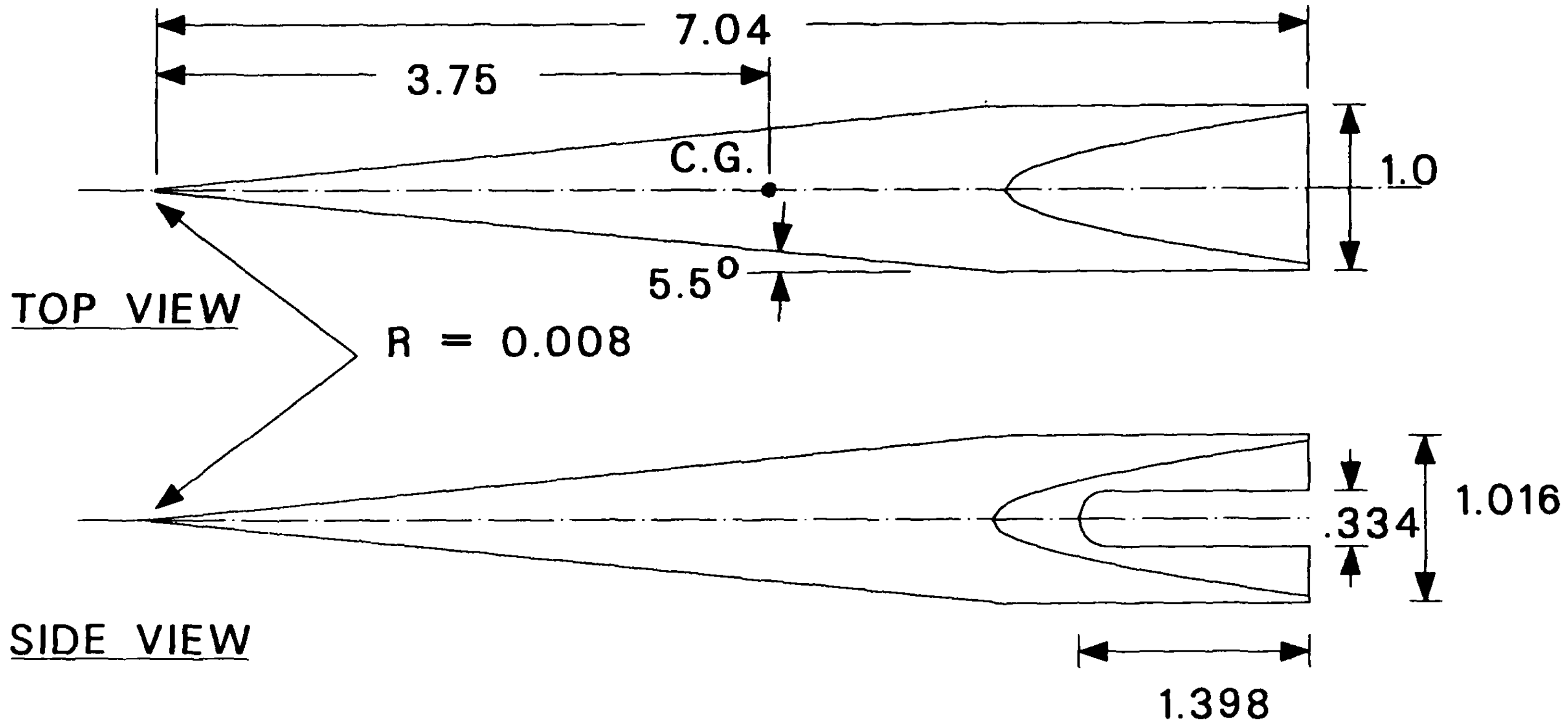
2. FOREBODY DRAG

The zero-yaw forebody drag of the railgun projectile has been computed across the Mach number range of interest and is shown in Figure 13. Both the viscous and pressure components of forebody drag as well as the total forebody drag coefficient show a decreasing trend with Mach number. Tabulated values of these coefficients are shown in Appendix B.

The presence of the gap may reduce the viscous component of drag due to the reduction in the wetted surface area which is exposed to the high speed flow. The reduction in viscous drag over the portion of the body with the gap was estimated by reducing the local incremental viscous drag by the ratio of the surface area with and without the gap. The results showed a four to six percent decrease in the viscous drag, and a two to three percent decrease in the total forebody drag.

IV. CONCLUSIONS

The viscous flow field over the railgun configuration has been computed from Mach 2 to Mach 8. Solutions have been obtained at zero and two degrees angle of attack and pitch-plane aerodynamic coefficients and zero yaw drag coefficients have been obtained. Based on the analysis presented here, the projectile is statically stable. At the present time, a very limited set of aerodynamic range tests have been performed. These tests also indicate that the projectile is aerodynamically stable.



ALL DIMENSIONS IN CALIBERS (ONE CALIBER = 12.7 mm)

Figure 1. Schematic of railgun projectile.

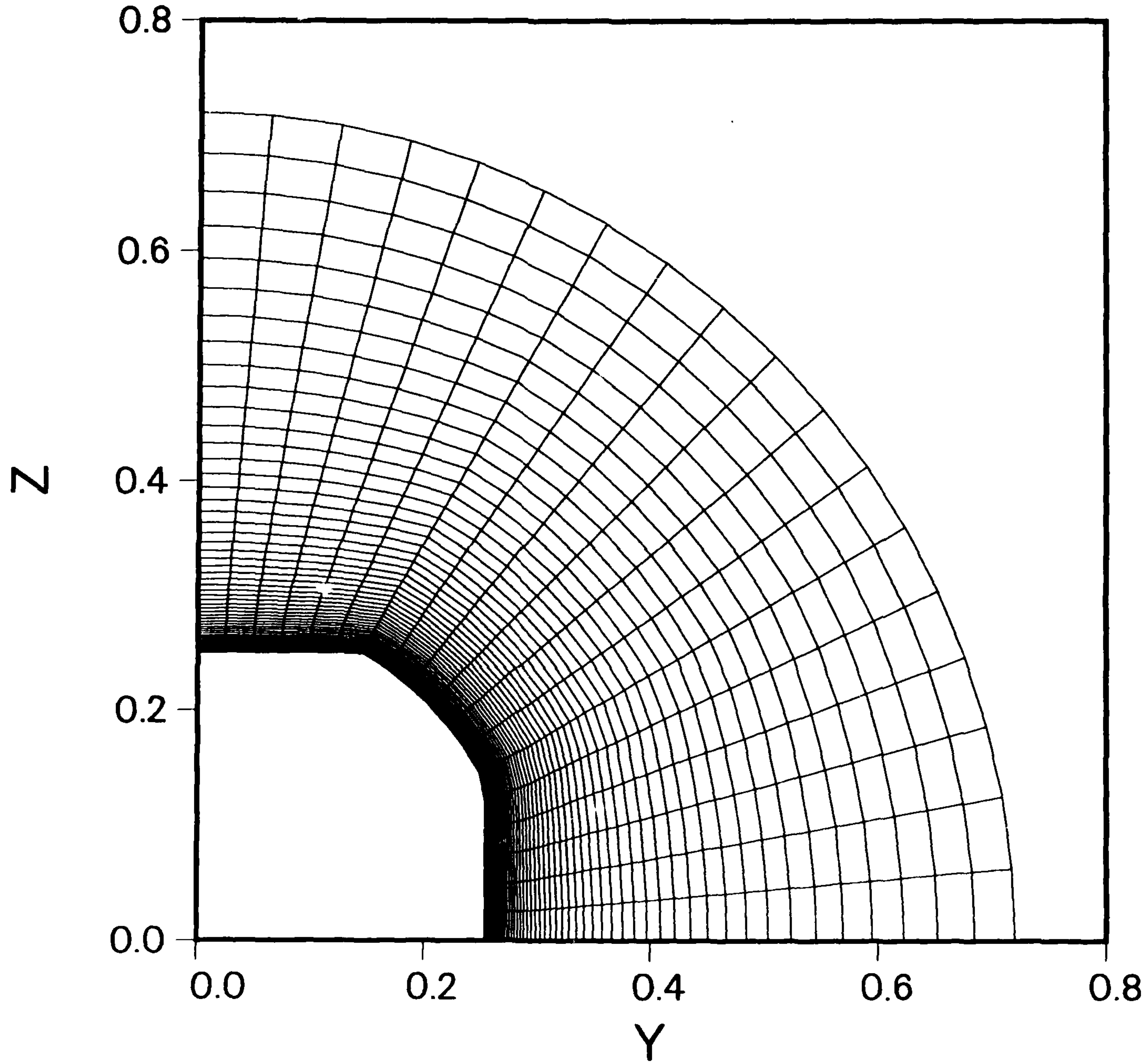


Figure 2. Portion of circumferential grid one caliber upstream of the base.

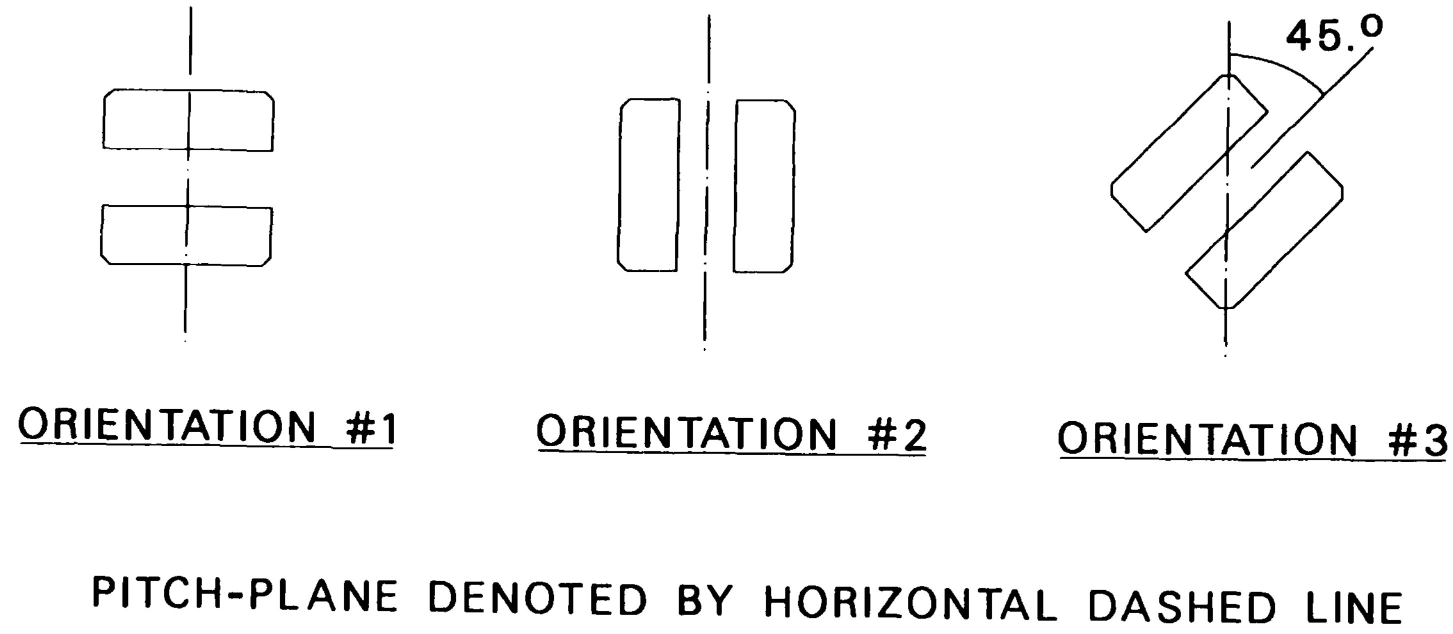


Figure 3. Projectile orientations with respect to pitch-plane.

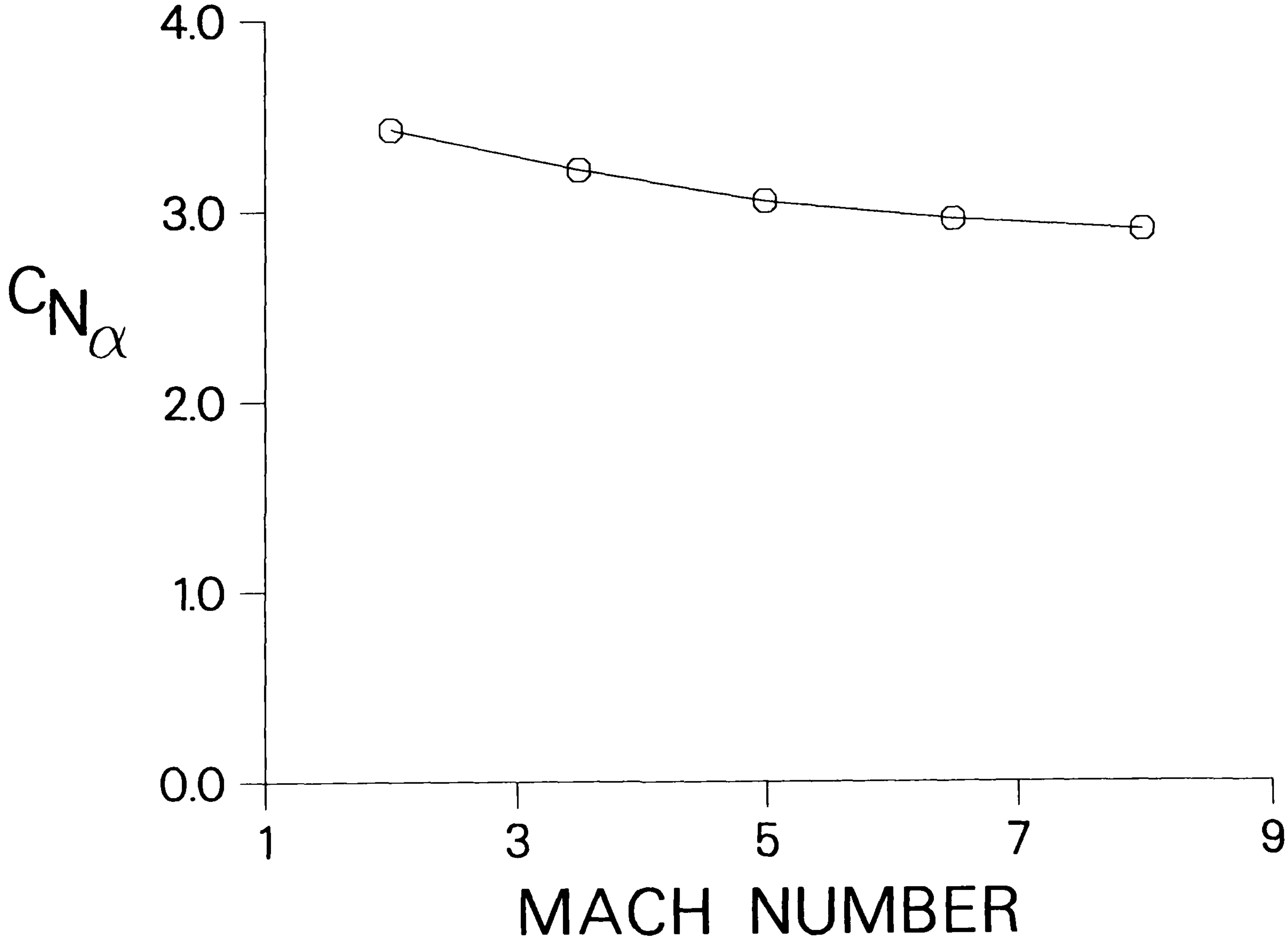


Figure 4. Variation of the slope of the normal force coefficient with Mach number - orientation 1.

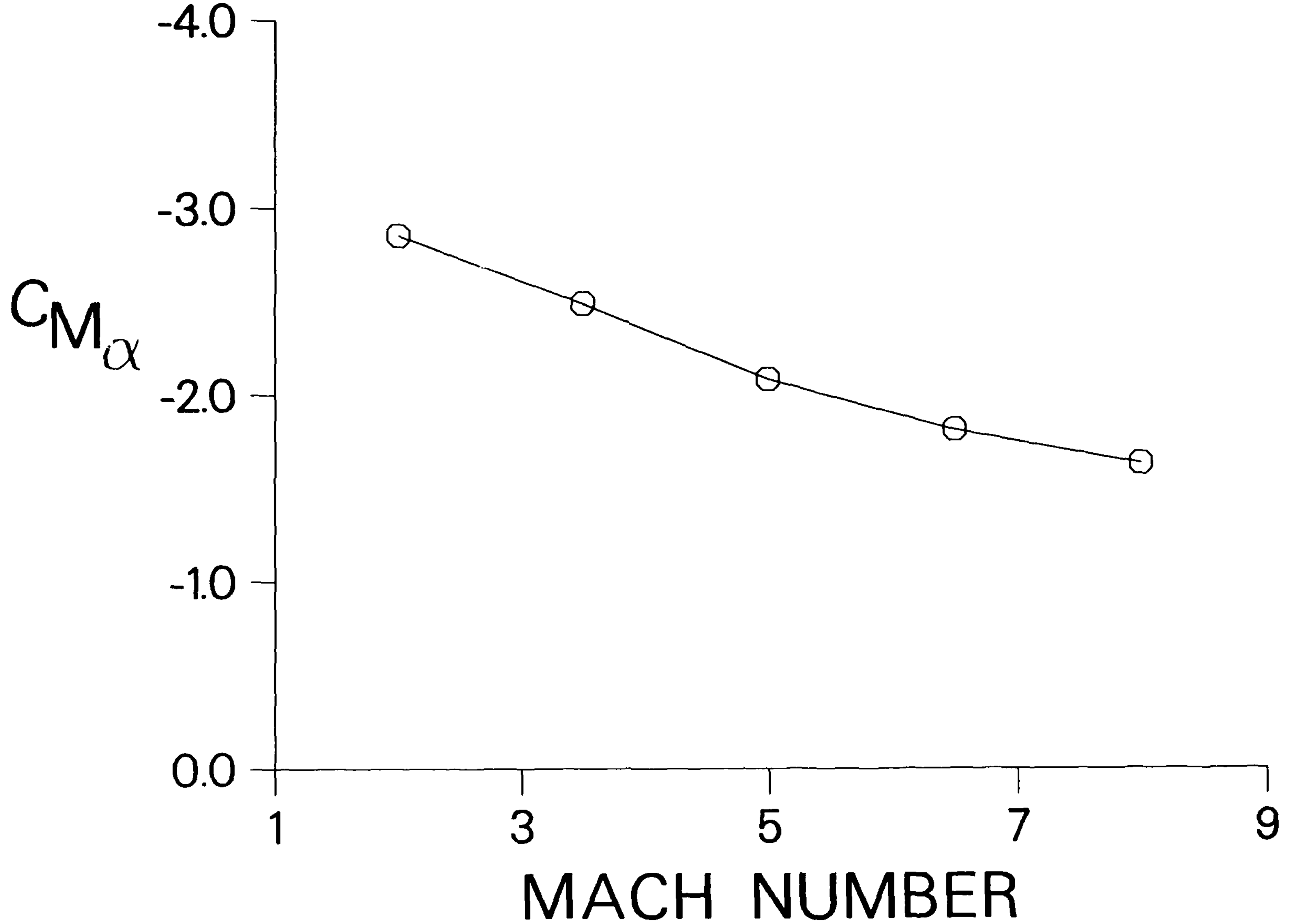
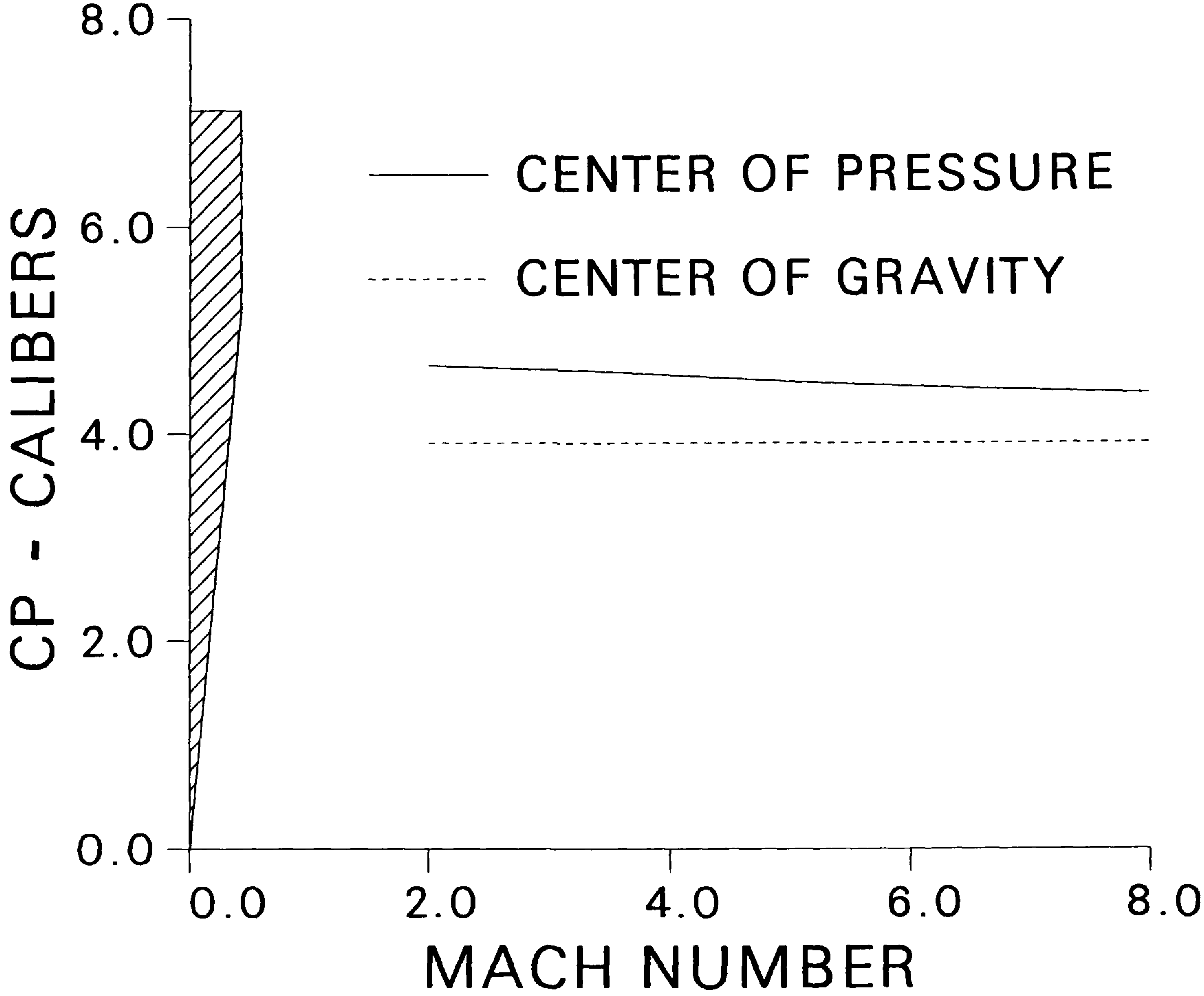


Figure 5. Variation of the slope of the pitching moment coefficient with Mach number - orientation 1.



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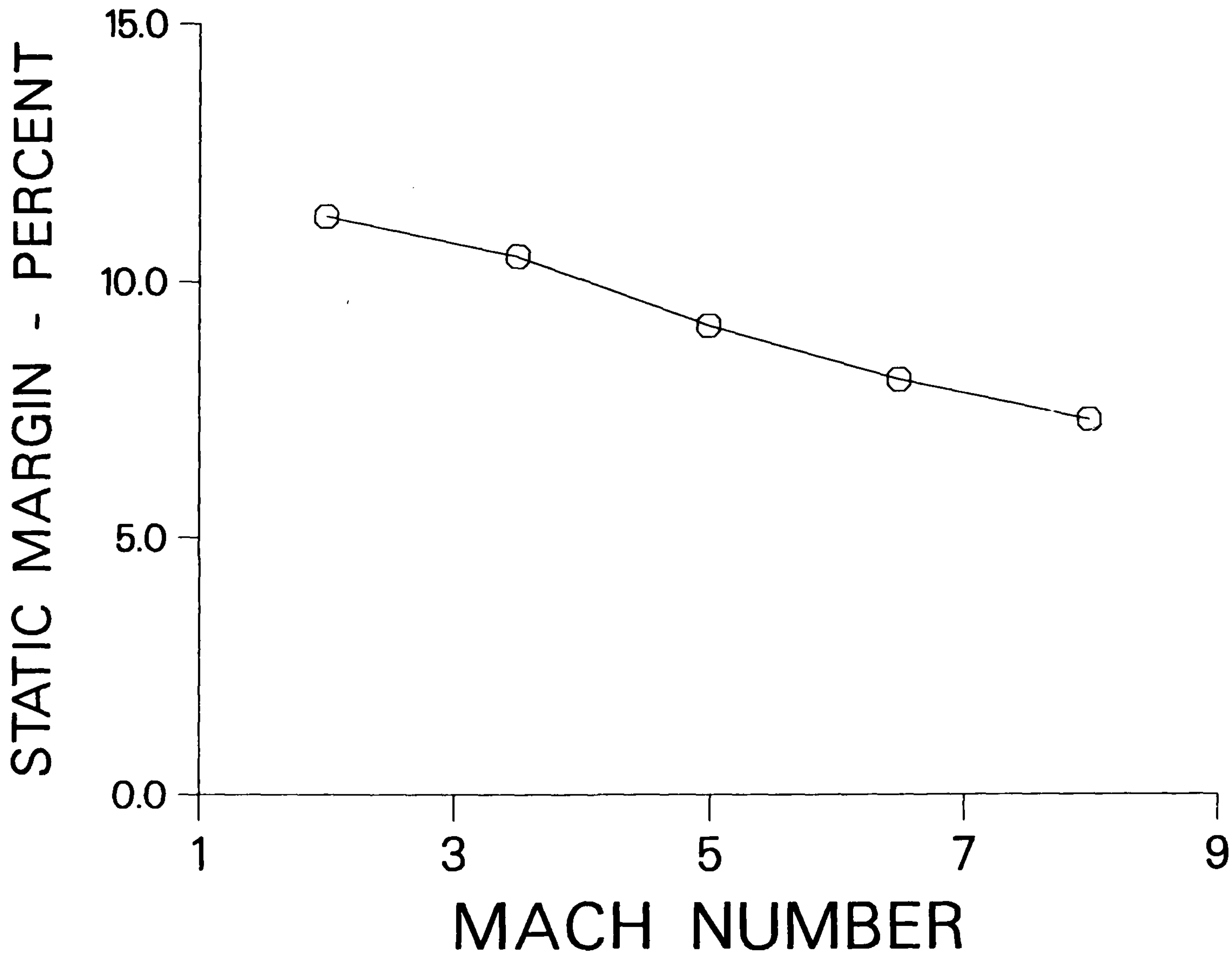

Figure 7. Variation of the static margin with Mach number - orientation 1.

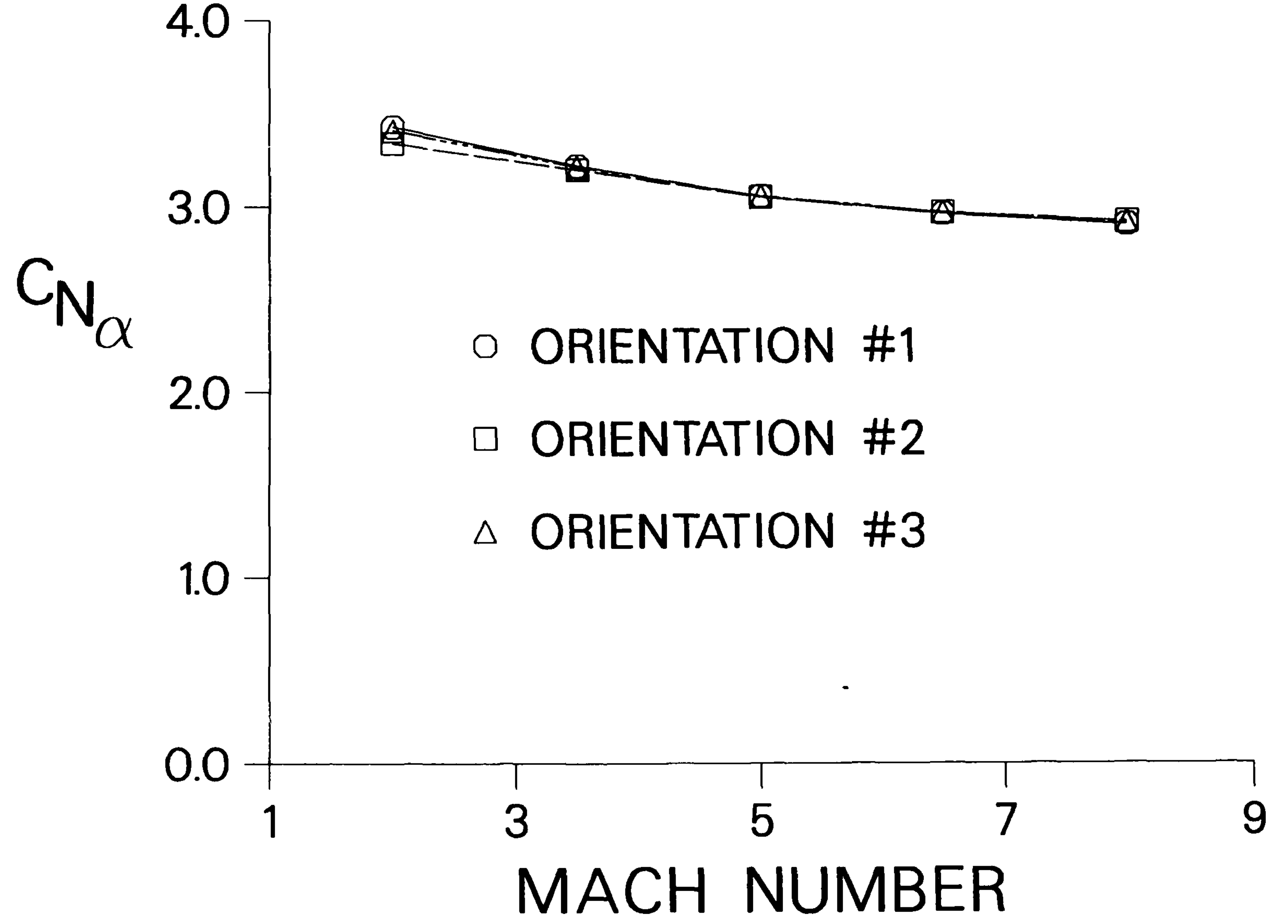

Figure 8. Variation of the slope of the normal force coefficient with Mach number - orientations 1, 2, and 3.

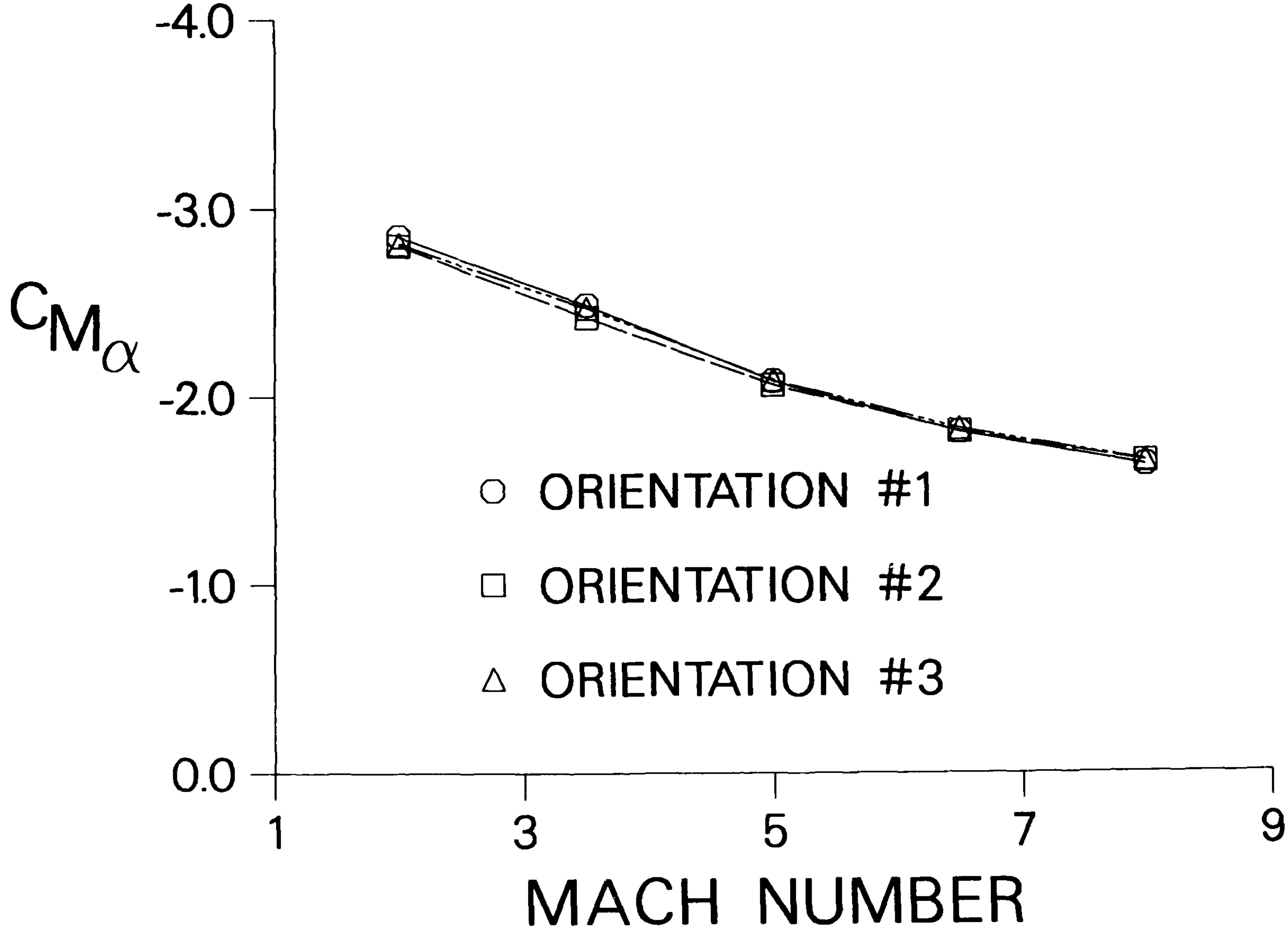

Figure 9. Variation of the slope of the pitching moment coefficient with Mach number - orientations 1, 2, and 3.

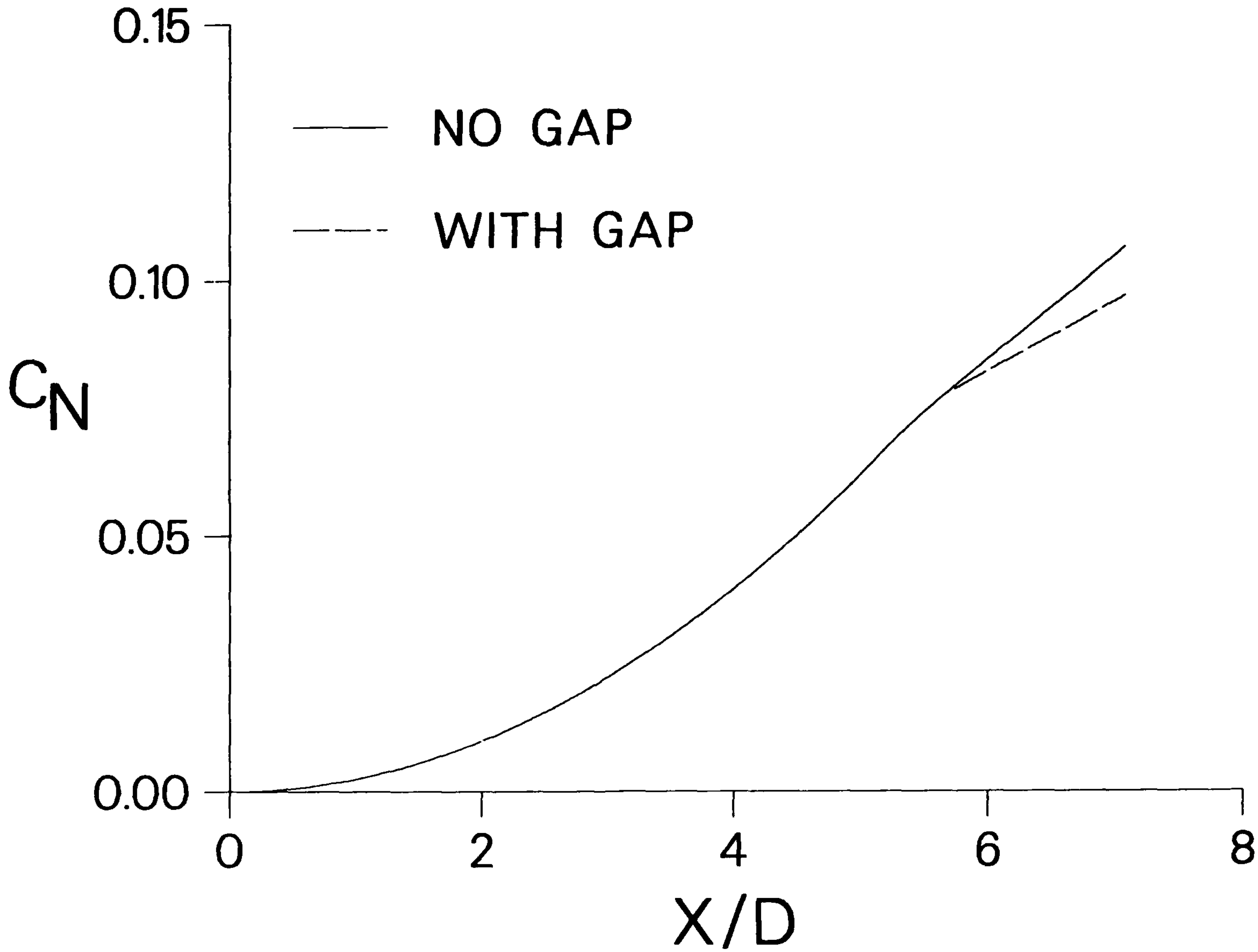

Figure 10. Development of normal force coefficient over the body with and without the gap.

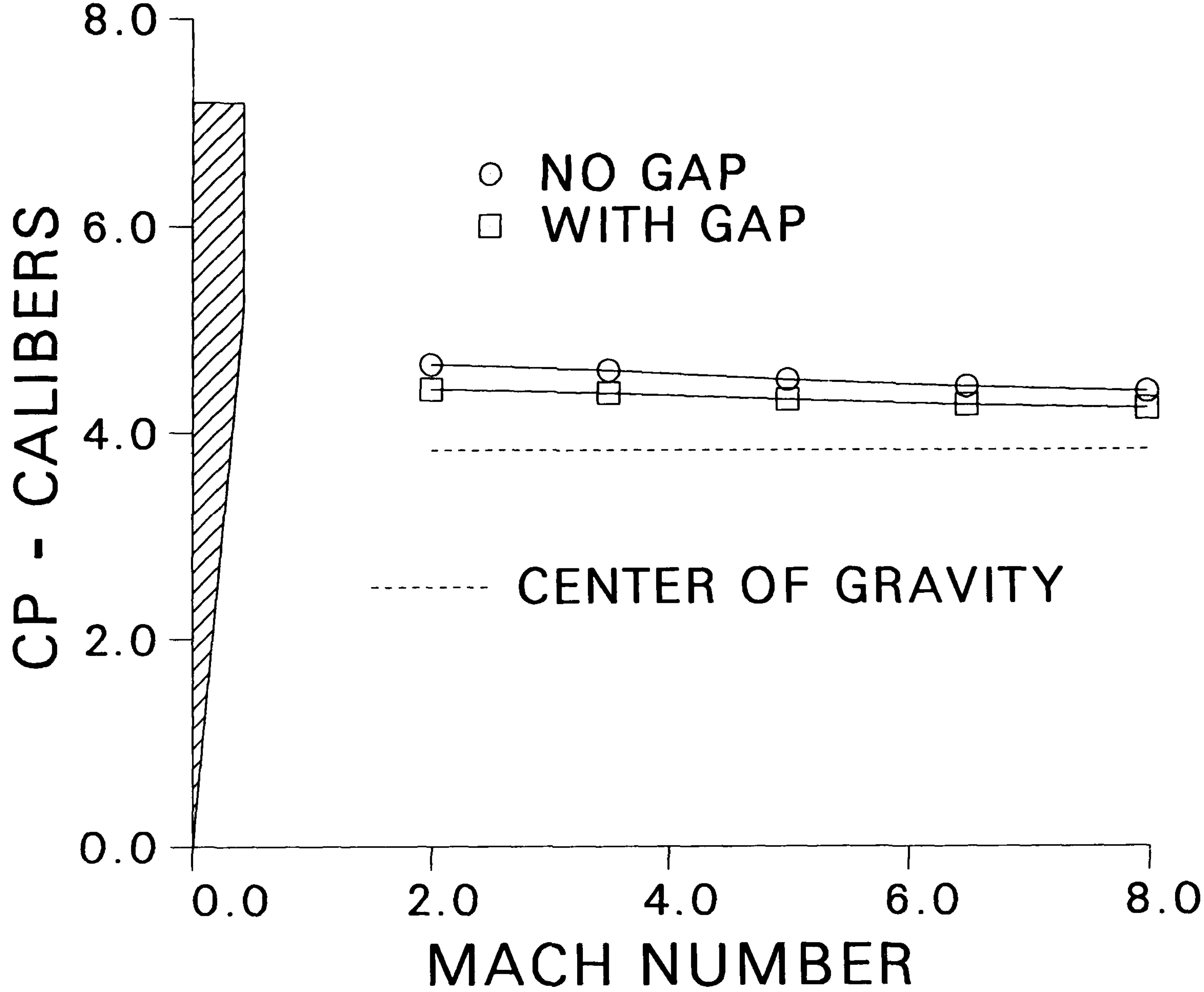

Figure 11. Variation of the center of pressure with Mach number with and without the gap.

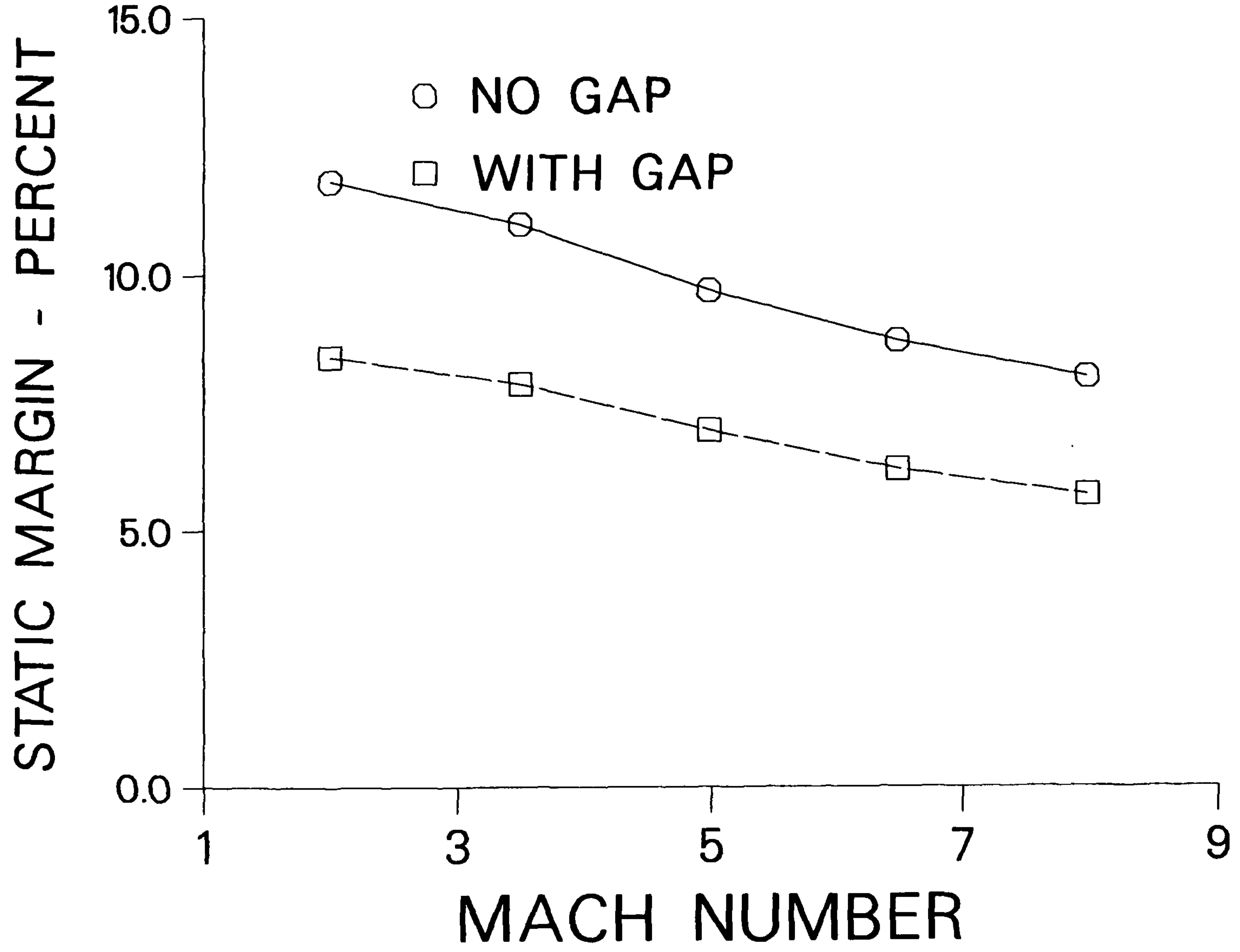

Figure 12. Variation of the static margin with Mach number with and without the gap.

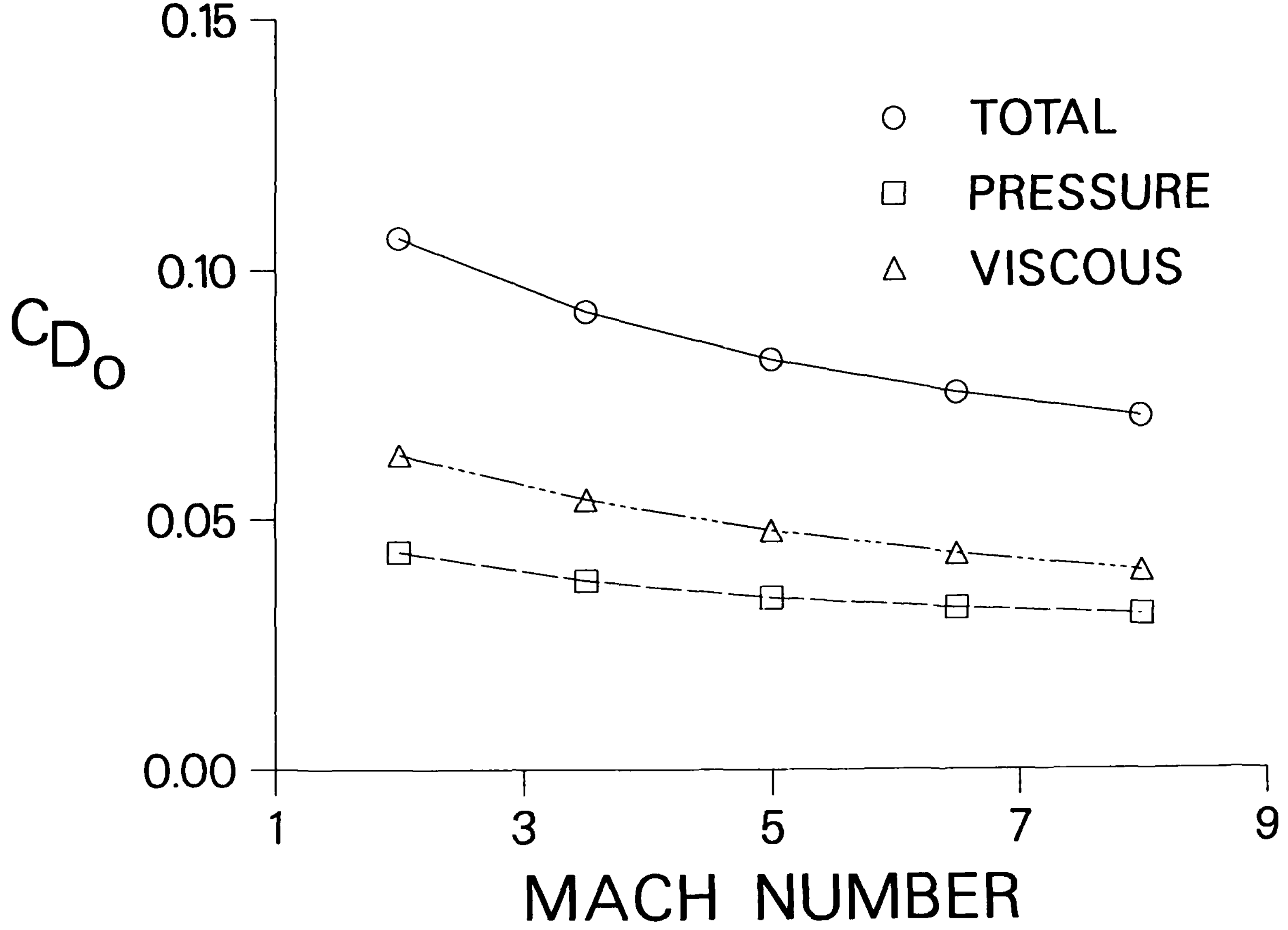

Figure 13. Variation of the zero-yaw forebody drag coefficient with Mach number.

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APPENDIX A

Table 1. Pitch-Plane Aerodynamics - Orientation 1

Mach Number	Slope of Normal Force Coefficient	Slope of Pitching Moment Coefficient Referenced To XCG	XCP/D From Cone Vertex	XCP/D From Nose	XCP/D From Base	STATIC MARGIN (Percent)
2.0	3.43	-2.85	4.66	4.58	2.46	11.8
3.5	3.22	-2.49	4.60	4.53	2.51	11.0
5.0	3.05	-2.08	4.51	4.43	2.61	9.7
6.5	2.96	-1.81	4.44	4.36	2.68	8.7
8.0	2.90	-1.63	4.39	4.31	2.73	8.0

Table 2. Pitch-Plane Aerodynamics - Orientation 2

Mach Number	Slope of Normal Force Coefficient	Slope of Pitching Moment Coefficient Referenced To XCG	XCP/D From Cone Vertex	XCP/D From Nose	XCP/D From Base	STATIC MARGIN (Percent)
2.0	3.34	-2.81	4.67	4.59	2.45	11.9
3.5	3.20	-2.42	4.59	4.51	2.53	10.8
5.0	3.05	-2.06	4.50	4.43	2.61	9.6
6.5	2.96	-1.81	4.44	4.36	2.68	8.7
8.0	2.91	-1.65	4.39	4.32	2.72	8.0

Table 3. Pitch-Plane Aerodynamics - Orientation 3

Mach Number	Slope of Normal Force Coefficient	Slope of Pitching Moment Coefficient Referenced To XCG	XCP/D From Cone Vertex	XCP/D From Nose	XCP/D From Base	STATIC MARGIN (Percent)
2.0	3.41	-2.82	4.65	4.58	2.46	11.7
3.5	3.21	-2.47	4.60	4.52	2.52	10.9
5.0	3.05	-2.09	4.51	4.44	2.60	9.7
6.5	2.96	-1.83	4.44	4.37	2.67	8.8
8.0	2.91	-1.65	4.40	4.32	2.72	8.1

Table 4. Pitch-Plane Aerodynamics - Gap Effect

Mach Number	Slope of Normal Force Coefficient	Slope of Pitching Moment Coefficient Referenced To XCG	XCP/D From Cone Vertex	XCP/D From Nose	XCP/D From Base	STATIC MARGIN (Percent)
2.0	3.02	-1.78	4.42	4.34	2.70	8.4
3.5	2.88	-1.59	4.38	4.31	2.73	7.9
5.0	2.78	-1.36	4.32	4.24	2.80	7.0
6.5	2.72	-1.19	4.26	4.19	2.85	6.2
8.0	2.69	-1.08	4.23	4.15	2.89	5.7

APPENDIX B

Table 5. Zero-Yaw Drag Coefficient

Mach Number	Total Forebody Drag	Forebody Drag Pressure Component	Forebody Drag Viscous Component
2.0	0.1064	0.0434	0.0630
3.5	0.0917	0.0377	0.0540
5.0	0.0820	0.0343	0.0478
6.5	0.0753	0.0322	0.0431
8.0	0.0705	0.0309	0.0396

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